

PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau



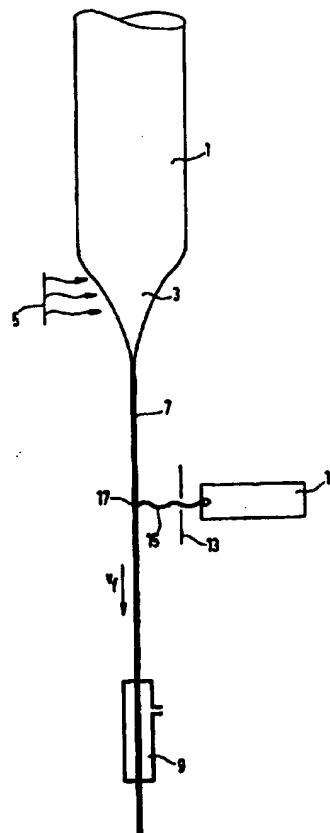
INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁶ : C03B 37/027, C03C 25/00, 25/02, G02B 6/16	A1	(11) International Publication Number: WO 96/23739 (43) International Publication Date: 8 August 1996 (08.08.96)
(21) International Application Number: PCT/IB96/00060 (22) International Filing Date: 25 January 1996 (25.01.96) (30) Priority Data: 95200239.2 1 February 1995 (01.02.95) EP (34) Countries for which the regional or international application was filed: NL et al. (71) Applicant: PLASMA OPTICAL FIBRE B.V. [NL/NL]; Zwaanstraat 1, NL-5651 CA Eindhoven (NL). (72) Inventor: GEERTMAN, Robert, Eugenio, Marie; Oranje Nassaulaan 17, NL-5503 JC Veldhoven (NL). (74) Agent: STOLK, Steven, A.; Internationaal Octrooibureau B.V., P.O. Box 220, NL-5600 AE Eindhoven (NL).		(81) Designated States: CN, JP, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE). Published <i>With international search report.</i>

(54) Title: OPTICAL FIBER HAVING REDUCED POLARISATION MODE DISPERSION

(57) Abstract

A method of manufacturing an optical fiber comprising a core portion with a dopant and a surrounding optical cladding portion, comprising the steps of drawing a fiber (7) from a molten extremity (3) of a silica preform (1) and moving the fiber (7) along means (9) for coating it with a protective sheath, whereby, prior to the coating step, the moving fiber (7) is irradiated with irregularly modulated actinic radiation (15), thereby causing corresponding irregular variations in the refractive index of its core portion as a function of longitudinal position. The resulting fiber demonstrates a significantly reduced polarisation mode dispersion.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AM	Armenia	GB	United Kingdom	MW	Malawi
AT	Austria	GE	Georgia	MX	Mexico
AU	Australia	GN	Guinea	NE	Niger
BB	Barbados	GR	Greece	NL	Netherlands
BE	Belgium	HU	Hungary	NO	Norway
BF	Burkina Faso	IE	Ireland	NZ	New Zealand
BG	Bulgaria	IT	Italy	PL	Poland
BJ	Benin	JP	Japan	PT	Portugal
BR	Brazil	KE	Kenya	RO	Romania
BY	Belarus	KG	Kyrgyzstan	RU	Russian Federation
CA	Canada	KP	Democratic People's Republic of Korea	SD	Sudan
CF	Central African Republic	KR	Republic of Korea	SE	Sweden
CG	Congo	KZ	Kazakhstan	SG	Singapore
CH	Switzerland	LI	Liechtenstein	SI	Slovenia
CI	Côte d'Ivoire	LK	Sri Lanka	SK	Slovakia
CM	Cameroon	LR	Liberia	SN	Senegal
CN	China	LT	Lithuania	SZ	Swaziland
CS	Czechoslovakia	LU	Luxembourg	TD	Chad
CZ	Czech Republic	LV	Latvia	TG	Togo
DE	Germany	MC	Monaco	TJ	Tajikistan
DK	Denmark	MD	Republic of Moldova	TT	Trinidad and Tobago
EE	Estonia	MG	Madagascar	UA	Ukraine
ES	Spain	ML	Mali	UG	Uganda
FI	Finland	MN	Mongolia	US	United States of America
FR	France	MR	Mauritania	UZ	Uzbekistan
GA	Gabon			VN	Viet Nam

"Optical fiber having reduced polarisation mode dispersion"

The invention relates to a method of manufacturing an optical fiber comprising a core portion with a dopant and a surrounding optical cladding portion, comprising the steps of drawing a fiber from a molten extremity of a silica preform and moving the fiber along means for coating it with a protective sheath. In particular, the
5 invention relates to an optical fiber having reduced polarisation mode dispersion.

The term "polarisation mode dispersion" (PMD) refers to the dispersion of signals carried by an optical fiber (particularly a single mode fiber), as a result of birefringence in the fiber's core portion. This birefringence is caused by imperfections in the fiber, such as slight non-circularity of its core cross section, asymmetrical lateral stress, *etc.*, and
10 manifests itself in dissimilar refractive indices for a carried signal's two orthogonal polarisation modes. In the case of a perfect fiber devoid of PMD, these two modes propagate independently of one another at a common velocity. However, in the presence of PMD, the relative phase of the two modes changes continually, returning to a particular configuration at certain spatial intervals along the fiber. The average such interval is referred to as the beat
15 length L_p of the fiber, and has a typical magnitude of the order of 1 m (meter).

A method as stated in the opening paragraph is known from United States Patent US 5,298,047, wherein, subsequent to the fiber coating step, the moving fiber is
20 caused to pass over a series of pulleys. By continually canting the rotational axis of at least one of these pulleys back and forth in an irregular manner (*i.e.* with a variable frequency), the fiber is subjected to an oscillatory torque which causes the entire length of fiber between the canting pulley and the preform to twist back and forth. Such twisting of warm, uncoated fiber impresses an oscillatory axial spin upon its constituent material, and this spin
25 subsequently becomes "frozen" into the fiber as it cools. The deliberate presence of such variable spin-related stress in the fiber produces continual mode-coupling between the orthogonal polarisation modes of a carried signal, thereby inhibiting the accumulation of a significant phase lag between the two modes, and consequently causing a significant reduction in the fiber's PMD.

It is an object of the invention to provide an alternative method by which an optical fiber having reduced PMD can be manufactured. In particular, it is an object of the invention that the specific means of achieving the said reduction in PMD should not necessitate mechanical contact with the fiber. Moreover, it is an object of the invention that the furnished alternative method be relatively cheap and easy to implement in existing fiber drawing arrangements. Specifically, it is an object of the invention to provide an optical fiber in which a significantly reduced PMD is achieved by a mechanism other than the presence of variable spin-related mechanical stress in the fiber.

These and other objects are achieved according to the invention in a method of manufacturing an optical fiber comprising a core portion with a dopant and a surrounding optical cladding portion, comprising the steps of drawing a fiber from a molten extremity of a silica preform and moving the fiber along means for coating it with a protective sheath, characterised in that, prior to the coating step, the moving fiber is irradiated with irregularly modulated actinic radiation, thereby causing corresponding irregular variations in the refractive index of its core portion as a function of longitudinal position.

The term "silica" is here intended to refer to any form of SiO_2 , whether amorphous or crystalline, synthetic or natural; the skilled artisan will understand that such silica typically comprises relatively small quantities of certain dopants (such as F or Ge, for example) so as to modify its refractive index. The term "actinic radiation" as here employed should be interpreted as referring to such forms of radiation as ultra-violet (UV) radiation, X-rays, electron beams, *etc.*, as well as to visible electromagnetic radiation of relatively short wavelength, such as green or blue light. Such radiation is here considered to be "modulated" when its intensity, wavelength or energy per particle are temporally varied, either directly at the source or with the aid of temporally adjustable eclipsing or deflecting means, such as a shutter. Such modulation is regarded as being "irregular" when the temporal separation of adjacent local maxima is not constant, so that the corresponding refractive index variations along substantial lengths of the fiber core do not occur at constant intervals.

It should be understood that the inventive exposure to modulated actinic radiation preferably occurs along substantially the entire length of optical fiber drawn in one go from the preform (typically of the order of 100 km), or at least along a plurality of individual portions of substantial length (of the order of 10-100 m) with possible interposed

portions of non-irradiated fiber.

The invention draws from the insight that, when exposed to actinic radiation of an appropriate energy, the electronic structure of dopants in the fiber's core portion can be altered in such a way as to locally increase the refractive index of the doped core material in the irradiated portion concerned. When such localised refractive index changes are disposed at irregular intervals along the length of the fiber core (in accordance with the invention), they instigate continual mode-coupling between the different polarisation modes of a signal propagating within the core, with an attendant significant reduction in PMD. Because the inventive irradiation leads to a local *increase* in the refractive index n_{co} of the core portion, and because n_{co} is already larger than the refractive index n_{cl} of the surrounding optical cladding portion, the essential condition $n_{co} > n_{cl}$ for the occurrence of Total Internal Reflection in the fiber core is maintained.

As a specific example, in the case of a GeO_2 dopant distributed throughout a silica core, irradiation of ground-state Ge atoms with actinic radiation (such as UV radiation) can lead to partial production of stable Ge(1) and Ge(2) excited states, whereby the obtained value of the atomic ratio Ge:Ge(1):Ge(2) depends on the particular type of actinic radiation employed. As a consequence, the refractive index of the Ge-doped core portion increases. This process is elucidated in more detail in an article by Russell *et al.* in SPIE Conference Proceedings Vol. 1373 (1990), *Fiber Laser Sources and Amplifiers II*, pp 126-139.

Other core dopants whose electronic structure can be modified using actinic irradiation include, for example, P (phosphorous) and Al (aluminium).

It is a particular advantage that the means for enacting the inventive irradiation do not necessitate mechanical contact with the fiber, and can be embodied in a very compact form (such as, for example, a laser beam, arc lamp or thermionic gun).

The coating means referred to hereabove may be of any type suitable for application in the art of optical fiber manufacture. For example, such means may comprise a chamber through which the moving fiber is guided and into which a reactive hydrocarbon gas is introduced, the chamber being further provided with heating means (*e.g.* inductive or microwave heating means) for the purpose of warming the fiber, thereby serving to increase the rate of deposition of a solid hydrocarbon layer (out of the gas phase) onto the fiber's surface. The inventive irradiation process occurs prior to the coating step, since the employed actinic radiation might otherwise suffer absorption in the fiber's protective sheath.

It must be stipulated that it is not essential that the fiber be either soft or

warm during the inventive irradiation process. On the other hand, if the fiber retains some amount of heat for a short time after being drawn, this will not inhibit the inventive method, unless the temperature of the fiber is high enough to provoke de-excitation of excited dopant states (occurring above about 700°C in the case of UV-irradiated Ge dopants, for example).

5 A particularly effective PMD-reduction is obtained according to the invention when $d_m < L_p$, where d_m is the average longitudinal separation of neighbouring localised zones of increased n_m . Preferably, d_m is several times smaller than L_p ; for example, if $L_p = 2$ m, then d_m should preferably (but not essentially) have a maximum value of about 1 m, and favourably a value of about 0.3-0.4 m (approximately five modulations per beat
10 length). The obtained value of d_m will, of course, depend on the linear velocity v_f of the moving fiber and on the average modulation time t_f of the actinic radiation. For example, if $v_f = 10$ m/s, then t_f must have a value of 0.05 s in order to obtain $d_m = 0.5$ m. It should be noted that the term "average" is here intended to refer to the arithmetic average taken over a substantial length of the optical fiber (e.g. 100 m) or a substantial time interval (e.g. 10 s).

15 Although different types of actinic radiation are, in principle, suitable for application in the inventive method, there may be a practical preference for the use of electromagnetic radiation, since this can easily be produced at high intensity from a cheap and compact source, and can easily be modulated using, for example, a shutter or pulsed power supply. In particular, the inventors have achieved highly satisfactory PMD-reduction
20 in Ge-doped silica fibers with the aid of UV or blue/green light from a laser source of randomly-pulsed intensity. UV light is hereby understood to have a wavelength in the range 230-260 nm, and preferably a value of approximately 244 nm, and blue/green light should be considered as having a wavelength in the range 460-520 nm, and preferably an approximate value of either 488 or 514 nm.

25 Besides such random pulsing of the actinic radiation, there are several other possible ways of achieving the desired irregular modulation in accordance with the invention. For example, such modulation may take any of the following forms:

- (1) a constant-amplitude block, triangular or sinusoidal wave, whose frequency is modulated in a random manner;
- 30 (2) alternated pulse doublets and triplets of unequal temporal pitch;
- (3) a superposition of at least two periodic block functions having respective periods P_1 and P_2 such that the value of the ratio P_1/P_2 is not an integer.

This list of examples is by no means exhaustive, and is given merely for illustrative purposes.

The selected intensity of the employed actinic radiation will depend *inter alia* on the value of t , and the concentration of dopants in the core portion of the optical fiber, in view of the statistical nature of the radiative mechanism by which the electronic structure of the core dopants is altered. The skilled artisan will be capable of tailoring the applied radiative intensity to the particular parameters in a given manufacturing situation. In the case of UV or blue/green laser light, the inventors have obtained satisfactory results with laser powers of the order of 0.1-1 W.

10 The invention and its attendant advantages will be further elucidated with the aid of exemplary embodiments and the accompanying schematic drawings, not of uniform scale, whereby:

Figure 1 depicts a process of manufacture of an optical fiber in accordance with the invention;

15 Figure 2 shows some exemplary optical fibers in accordance with the invention, with a stylised representation of the longitudinal refractive index variations in their core portions.

20 Embodiment 1

Figure 1 depicts a procedure for manufacturing an optical fiber in accordance with the present invention.

A silica preform 1 is manufactured, for example, by depositing doped layers of synthetic silica on the inside surface of a silica substrate tube (*e.g.* using Plasma Chemical Vapour Deposition), and subsequently thermally collapsing the tube into a preform rod. By using different dopants (such as F (fluorine) and Ge (germanium)) during this deposition procedure, the resulting preform rod is thus embodied that its core silica has a higher refractive index than the silica in its outer reaches. For example, the rod may be manufactured in such a way that its outer regions (corresponding to the optical cladding portion of the drawn fiber) are doped with approximately 1 at.% F and 1 mol.% GeO_2 , whereas its core region (corresponding to the core portion of the drawn fiber) is doped with approximately 1 at.% F and 5 mol.% GeO_2 . If so desired, the resulting preform rod can be subsequently encased in a silica jacketing tube. In any case, the final product constitutes the

preform 1.

The manufacture of such a preform 1 can, of course, occur using a variety of their well known methods. The specific method used is of no particular importance to the subsequent enaction of the optical fiber manufacturing process in accordance with the invention, hereinafter further elucidated.

The preform rod 1 is heated at an extremity 3 using heating means 5. From this heated extremity 3, a fiber 7 is drawn away with a linear velocity v_f . This fiber comprises a central core portion which is surrounded by an optical cladding portion. The fiber 7 is subsequently moved through coating means 9, where it is provided with a protective sheath (*e.g.* an opaque polymer coating).

At a location between the extremity 3 and the coating means 9, the moving fiber 7 is locally irradiated with irregularly modulated actinic radiation 15. As here depicted, the radiation beam 15 is derived from a spatially fixed source 11 which is located behind a shutter 13. In a particular example, the beam 15 comprises blue/green light, the source 11 is a 0.2 W Ar laser beam of substantially constant intensity, and the shutter 13 is abruptly opened and closed in a random manner (*e.g.* by controlling it with a servo device operating with a duty cycle which is determined by a processor unit acting as a random number generator); in this way, the moving fiber 7 is subjected to random pulses (or blocks) of blue/green light.

At points 17 where the beam 15 intercepts the fiber 7, the refractive index n_{co} of the core portion of the fiber 7 will be increased. This increase in n_{co} will, of course, occur along the whole trajectory of the fiber 7 exposed to any given dose (*i.e.* pulse or block) of actinic radiation 15. For example, if $v_f = 10$ m/s and the shutter 13 is opened for an interval of 0.005 s, then the length of the fiber 7 thus exposed to actinic radiation will be 10×0.005 m = 0.05 m = 50 mm, so that n_{co} will increase along a length 50 mm.

Assuming a GeO_2 dopant concentration of 5 mol.% and an intensity of 0.2 W for the beam 15, the refractive index n_{co} will typically increase by about 0.01 % upon irradiation.

30

Embodiment 2

Figure 2 depicts segments of three optical fibers 37, 47, 57 manufactured in accordance with different possible variants of the current inventive method. These fibers

comprise respective core portions 371, 471, 571 which are surrounded by respective optical cladding portions 373, 473, 573. The fibers' protective sheaths are not depicted in the Figure, for the sake of clarity. As a specific example, the core portions 371, 471, 571 may comprise Ge-doped silica, and the optical cladding portions 373, 473, 573 may comprise F-doped silica.

The refractive index n_{co} of each core portion 371, 471, 571 exceeds the refractive index n_{cl} of the corresponding optical cladding portion 373, 473, 573. However, n_{co} does not have a constant value as a function of longitudinal position along the different fibers 37, 47, 57. Instead, each of the fiber core portions 371, 471, 571 respectively comprises irregularly spaced zones 375, 475, 575 (shaded in the Figure) in which n_{co} demonstrates a local maximum value, with intervening zones 377, 477, 577 (not shaded) where n_{co} has a locally lower value. The irregularly spaced zones 375, 475, 575 are preferably disposed along substantially the whole length (typically of the order of 100 km) of the respective fibers 37, 47, 57, or at least disposed along several very substantial lengths (of the order of 10-100 m) thereof.

In the case of fiber 37, the zones 375 all have the same length h , but are disposed at variable separations in the longitudinal direction, *i.e.* the zones 377 are not of constant length. Such a pattern of zones 375, 377 can be achieved in an embodiment of the inventive method whereby the actinic radiation is modulated according to a block function comprising on-blocks of constant temporal duration disposed at random temporal intervals.

In fiber 47, neither the zones 475 nor the zones 477 are of constant length. However, the pattern of zones 475, 477 demonstrates a certain periodicity, since it repeats itself after each set of three consecutive zones 475. Such periodicity may be obtained in an embodiment of the inventive method whereby constant-intensity actinic radiation is directed onto the moving fiber *via* an eclipsing device comprising a continually rotating disc with three different azimuthal apertures.

In the case of fiber 57, there is no periodicity in the pattern of zones 575, 577. Such a pattern may be achieved in an embodiment of the inventive method whereby the actinic radiation is derived from a randomly pulsed source.

As here depicted, all the shaded zones are sharply delimited by abrupt borders. In practice, however, there may also be a gradual fluctuation in n_{co} , so that the obtained patterns are less discontinuous in appearance (as in the case of frequency-modulated sinusoidal irradiation, for example).

CLAIMS:

1. A method of manufacturing an optical fiber comprising a core portion with a dopant and a surrounding optical cladding portion, comprising the steps of drawing a fiber from a molten extremity of a silica preform and moving the fiber along means for coating it with a protective sheath, characterised in that, prior to the coating step, the moving
5 fiber is irradiated with irregularly modulated actinic radiation, thereby causing corresponding irregular variations in the refractive index of its core portion as a function of longitudinal position.
- 2 A method according to Claim 1, characterised in that the preform is thus selected that the core portion of the drawn fiber comprises Ge as the dopant.
- 10 3. A method according to Claim 1 or 2, characterised in that the type of actinic radiation is selected from the group comprising ultra-violet radiation and blue/green light.
4. A method according to any of the Claims 1-3, characterised in that the actinic radiation is derived from a randomly pulsed laser source.
- 15 5. An optical fiber comprising a core portion with a dopant and a surrounding optical cladding portion, characterised in that, along substantially its whole length, the refractive index of the core portion demonstrates significant irregular variations as a function of longitudinal position.

1/2

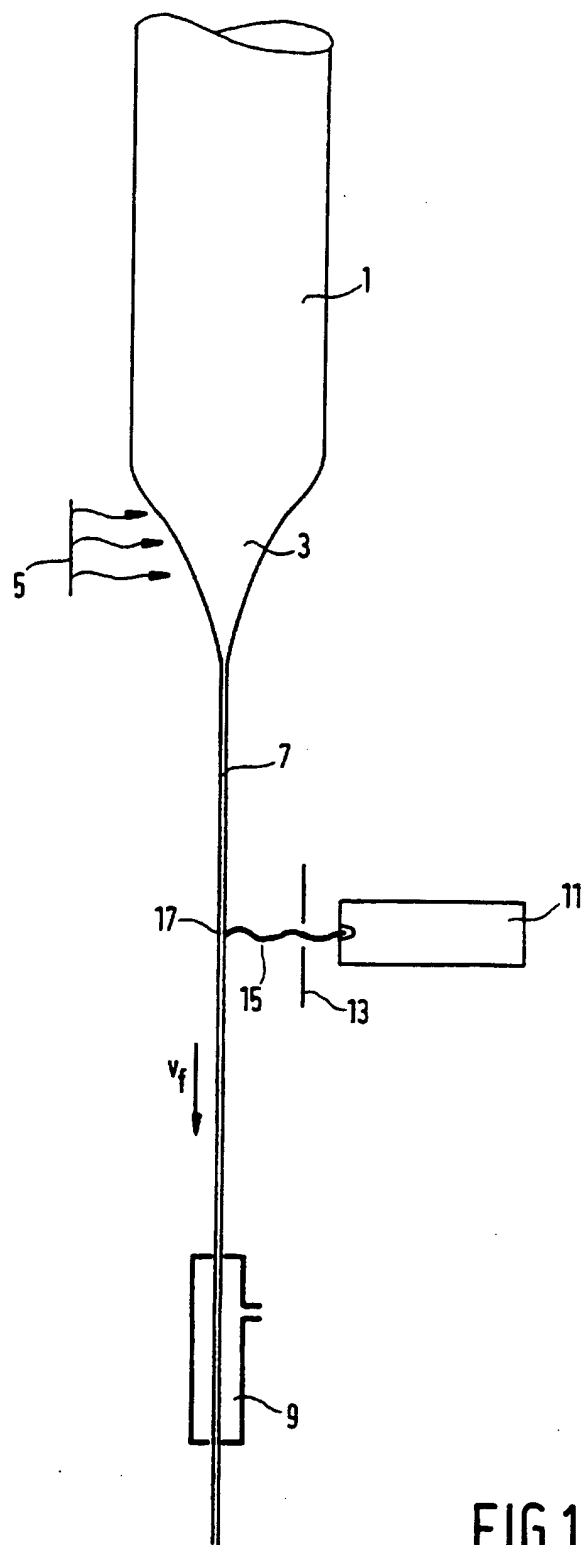


FIG.1

212

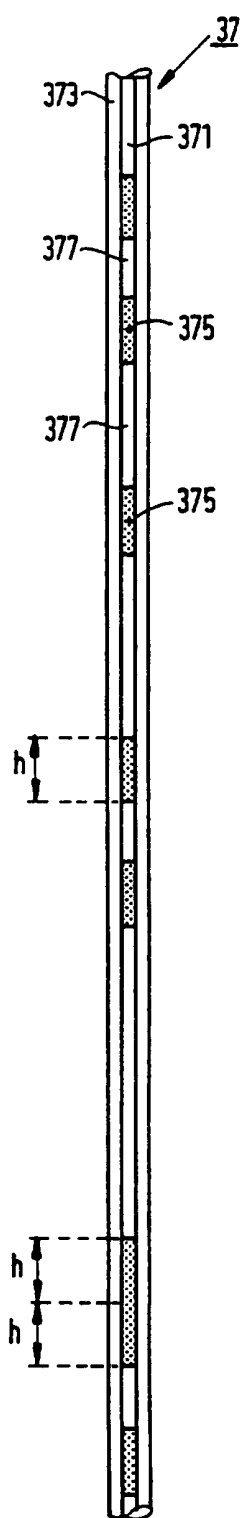


FIG. 2A

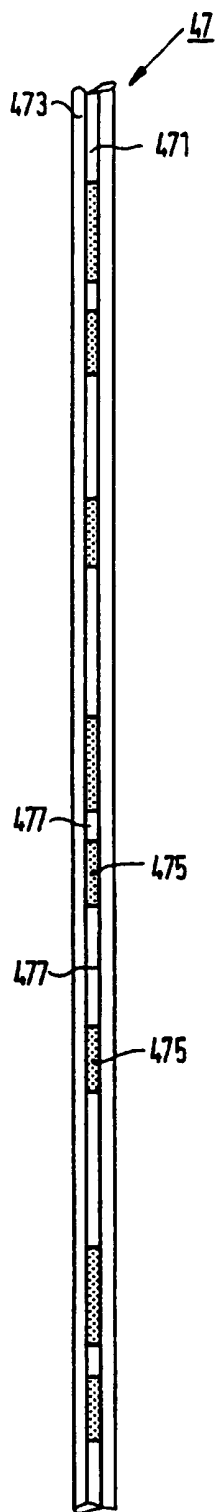


FIG. 2B

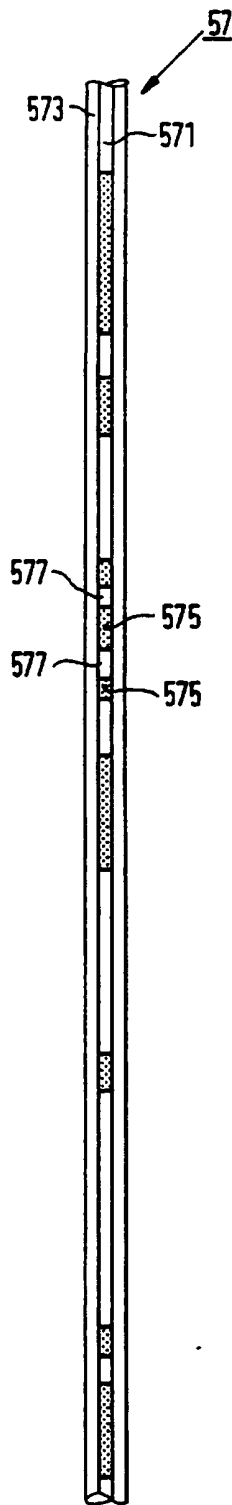


FIG. 2C

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IB 96/00060

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 C03B37/027 C03C25/00 C03C25/02 G02B6/16

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 C03B C03C G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	US,A,5 400 422 (C.G.ASKINS ET AL.) 21 March 1995 see column 4, line 48 - line 51; claims 1-5,9,10,15,25; figures 5,6; example 1 ---	1-5
X	WO,A,94 19713 (UNIVERSITY OF SOUTHAMPTON, GB) 1 September 1994 see page 6, line 10 - line 22; claims 1-8,10-12,15,22; figure 1 see page 7, line 24 - line 29 see page 11, line 33 - page 12, line 5 see page 13, line 17 - line 26 ---	1-5
X A	EP,A,0 604 039 (AT&T CORP.) 29 June 1994 see column 2, line 7 - line 18; claims 11-14 see column 4, line 4 - column 7, line 22 -----	5 1,3,4

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

- *A* document defining the general state of the art which is not considered to be of particular relevance
- *E* earlier document but published on or after the international filing date
- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

- *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- *&* document member of the same patent family

Date of the actual completion of the international search

19 March 1996

Date of mailing of the international search report

- 2 04. 96

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax (+31-70) 340-3016

Authorized officer

Stroud, J

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IB 96/00060

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A-5400422	21-03-95	NONE	
WO-A-9419713	01-09-94	GB-A- 2275347	24-08-94
EP-A-0604039	29-06-94	US-A- 5363239	08-11-94
		EP-A- 0631158	28-12-94
		JP-A- 6230208	19-08-94